APPLICABILITY OF DURABILITY REQUIREMENTS OF THE EUROPEAN STANDARD EN 206-1 TO SELF-COMPACTING CONCRETE

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ABSTRACT

Durability and more specifically carbonation and chloride penetration, is of major importance for reinforced concrete structures. Before using self-compacting concrete (SCC), the carbonation and chloride penetration has to be investigated in order to locate and prevent possible problems. In order to do so, an extended experimental programme was set up simulating real conditions. This project includes laboratory experiments on the carbonation and chloride penetration of 14 self-compacting concrete (SCC) mixtures. For the carbonation study, these concretes were stored alternately one week in a carbonation room at 20°C, 60% R.H. and 10% CO_2 and one week immersed in water. For the chloride penetration study, cylindrical specimens with a diameter of 230mm and a height of 70mm were alternately immersed in a solution containing chlorides and exposed to air. One cycle took approximately 1 hour.

In Belgium, no standards are available for self-compacting concrete. For this reason, the results of this experimental study are compared with the European Standard EN 206-1: 2001 concerning 'Concrete – Specification, performance, production and conformity' and the National Application Document NBN B15-001: 2004 of this European Standard. Both are only applicable to traditional concrete and combine a maximum W/C ratio and a minimum cement content, both depending on the environment. An optional minimum compressive strength is mentioned.

This comparison leads to the conclusion that self-compacting concrete meets the durability requirements prescribed for traditional concrete. Based on the experimental results, the combination of a maximum W/C ratio and a minimum cement content is also a requirement for self-compacting concrete. The requirement for a minimum compressive strength is also optional for self-compacting concrete. In case of self-compacting concrete there is always a large positive difference between the minimum and real compressive strength.

INTRODUCTION

The Standard EN 206-1:2001 'Concrete – Specification, performance, production and conformity' and the National Application Document NBN B15-001: 2004, describe normative durability requirements for vibrated concrete depending on the environment. Self-compacting concrete is outside the scope of the standard and in Belgium no standards are available specifically for SCC.

For this reason, the applicability of these standards to self-compacting concrete with respect to carbonation and chloride penetration was verified experimentally on 14 SCC mixes with different parameters: W/C ratio, amount of cement, amount of water, amount of powder,… The test specimens were prepared using three Portland cements (of different strength classes) and 2 limestone fillers (with different grading curves).

EXPERIMENTAL PROGRAM

Concrete compositions

The concrete compositions of the different concrete mixes is given in Table 1, together with the compressive strength class and the concrete type as defined in the European Standard EN 206-1: 2001 and the National Application Document NBN B15-001: 2004. The compressive strength class was determined based on test results on concrete cubes with a side length of 150 mm. A standard deviation of 5N/mm² was assumed in order to calculate the characteristic compressive strength. The determination of the concrete type is based on the W/C ratio and the amount of cement. For each concrete type, there is an optional requirement of minimum compressive strength. In all cases, this requirement was met.

Table 1. Concrete compositions, compressive strength classes, concrete types and experimental coefficients

	CEM I 42.5 R [kg/m³]	CEM I 52.5 [kg/m³]	CEM I 52.5 HSR [kg/m³]	limestone filler S [kg/m³]	limestone filler P2 [kg/m³]	water [kg/m³]	sand 0/5 [kg/m³]	gravel 4/14 [kg/m³]	gravel 2/14 [kg/m³]	W/C [-]	Strength class	Concrete type	A_1 [mm/√year]	H [mm/√cycle]
SCC1	360				240	165	853	698		0.46	C35/45	T(0,50)	1.65	0.23
SCC2		360			240	165	853	698		0.46	C45/55	T(0,50)	1.05	0.19
SCC3			360		240	165	853	698		0.46	C50/60	T(0,50)	1.81	0.20
SCC4	360			240		165	853	698		0.46	C35/45	T(0,50)	2.13	0.22
SCC5	300				300	165	853	698		0.55	C30/37	T(0,55)	2.51	0.30
SCC6	400				200	165	853	698		0.41	C45/55	T(0,45)	2.13	0.19
SCC7	450				150	165	853	698		0.37	C50/60	T(0,45)	1.30	0.16
SCC8	300				200	137	923	755		0.46	C40/50	T(0,55)	2.86	0.21
SCC9	400				300	192	782	640		0.48	C40/50	T(0,50)	1.68	0.25
SCC10	450				350	220	712	583		0.49	C30/37	T(0,50)	1.49	0.28
SCC11	360				240	144	865	707		0.40	C50/60	T(0,45)	1.21	0.17
SCC12	360				240	198	835	683		0.55	C30/37	T(0,55)	3.43	0.27
SCC13	360				240	216	825	675		0.60	C25/30	T(0,60)	4.63	0.32
SCC14	360				240	165	816		734	0.46	C50/60	T(0,50)	0.73	0.21

Description of test methods

The carbonation coefficients were experimentally determined on concrete cubes with side length 100 mm. These concrete cubes were stored in an environmental room at 20°C ± 2 °C and more than 90% R.H. At the age of 28 days, an epoxy coating was applied to all surfaces, except for the surface that was to be exposed to CO_2. The concrete cubes were stored alternately one week in the carbonation room at 20°C, 60% R.H. and 10 vol.% CO_2 and one week immersed in water. At regular times (8, 12, 16, 20 and 24 weeks) the carbonation depth was determined. At each time, a slice with a thickness of 1 cm was sawn from each specimen. This slice was sprayed with a phenolphthalein solution in order to determine the carbonated zone. This pH indicator changes from colourless to purple as the pH rises from 8.3 to 10.0. The test indicates the depth to which the $Ca(OH)_2$ has been depleted. After the sawing of the slices, the remaining concrete specimen was covered again with the epoxy coating and the treatment continued. This test procedure corresponds with Exposure Class XC4 'Cyclic wet and dry – concrete surfaces subject to water contact' form the European Standard EN 206-1: 2001. From the measured penetration depths, the

carbonation coefficient A was determined and recalculated to an environment with a CO_2 concentration of 1% (industrial environment). More information on the experiments is given in other publications (1,2,3,4).
The chloride penetration depth was experimentally determined with a testing device consisting of horizontal rotating axes, which allowed for immersion of cylindrical concrete specimens (with a diameter of 230 mm and a thickness of 70 mm) in a chloride solution, followed by exposure to a dry environment (air). One cycle took approximately 1 hour, 1/3 wetting and 2/3 drying. The chloride solution of 3.5% of NaCl in water is kept in a container below the specimen. The depth and location of the container were such that about 50 mm of the outer part of the specimen was wetted. In this way, each point of the outer circumference is submersed during 1/3 of the rotation time. A photo of the testing apparatus is shown in Figure 1. From each of the mixes, 6 cylindrical specimens were made and stored in a climate room at 20 °C ± 2 °C and more than 90% R.H.. At the age of 28 days, the specimens were mounted on the testing device. After 6 weeks the first specimen was removed from the apparatus and broken in 3 pieces. Using the silver nitrate solution (5), the chloride penetration depth was determined at the freshly split section at 24 points. Measurements performed on one specimen resulted in 6 chloride penetration profiles. After 12 weeks, the second specimen is taken from the apparatus and tested. The next 4 specimens are tested at 18, 24, 30 and 36 weeks. More information on the chloride penetration tests is given in several other publications (1,6,7,8).

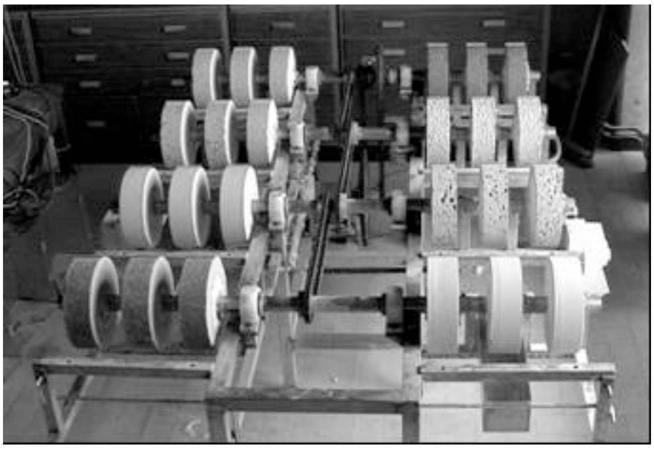

Figure 1. Testing device for cyclic testing

The measured depths of carbonation and chloride penetration were used to determine, respectively, the carbonation coefficient A and the chloride penetration coefficient H. Both processes can be considered as a Fickian problem because they are diffusion controlled processes and therefore governed by the equation:

$$x = (A \text{ or } H)\sqrt{t} \tag{1}$$

in which x is the carbonation or chloride penetration depth, t is the exposure time and A or H is a constant depending on the diffusion resistance of the material. In literature, most of the models are following this law, although some other models can be found. After the determination of A, this value was converted to A_1 for an industrial environment with 1% of CO_2 in the air. H is expressed in function of the number of cycles. The values of both constants determined for different mixes are given in Table 1.

VERIFICATION OF DURABILITY REQUIREMENTS

Introduction

The carbonation or chloride penetration depth at the end of the service life is calculated for a proposed service life duration of 50 years, together with an experimentally determined carbonation or chloride penetration coefficient. This value is compared with the concrete cover thicknesses. The concrete cover thicknesses from Table 4.2 of Eurocode 2 are used. The values for reinforced concrete are chosen because these are smaller, and by this more strict, than the concrete covers for prestressed concrete. For corrosion initiated by carbonation, the minimum concrete cover thickness is 20 mm or 25 mm, depending on the possibility of frost exposure. For this research the value of 20 mm was chosen because in the European Standard EN 206-1: 2001 no difference is made between frost and no-frost exposure for corrosion induced by carbonation. For chloride induced reinforcement corrosion, the concrete cover thickness is 40 mm.

Carbonation

In EN 206-1: 2001 and NBN B15-001: 2004 a type T(0,50) is prescribed for the exposure class XC4. This is a concrete with at least 320 kg/m³ of cement, a maximum W/C ratio of 0.50 and a minimal compressive strength class of C30/37.
For each concrete type, the experimental concrete mix with the largest carbonation coefficient was chosen (Table 1) and the penetration depth calculated. This maximum carbonation depth for each concrete type is given in Table 2. From this table, it is concluded that indeed a concrete type T(0,50) is needed to obtain a carbonation depth smaller than 20 mm.

Table 2. Maximum carbonation depth for different concrete types

		$x_{1\%}$ (mm)
T(0,45)	SCC6	15.1
T(0,50)	SCC4	15.1
T(0,55)	SCC12	24.1
T(0,60)	SCC13	32.6

In order to study the necessity to combine the requirements of a minimum cement content and a maximum W/C ratio, both factors are studied separately. In Table 3 and in Table 4, the maximum carbonation depth is given if, respectively, only the cement content or only the W/C ratio is considered.

Table 3. Maximum carbonation depth for different cement contents

C (kg/m³)		$x_{1\%}$ (mm)
300	SCC13	32.6
320	SCC13	32.6
340	SCC13	32.6

Table 4. Maximum carbonation depth for different W/C ratios

W/C (-)		$x_{1\%}$ (mm)
0,45	SCC6	15.1
0,50	SCC8	20.4
0,55	SCC12	24.1
0,60	SCC13	32.6

From Table 3, it is clear that using only a minimum cement content as unique requirement is not sufficient. Based on Table 4, the conclusion is that using only a maximum W/C ratio requirement is not sufficient. This illustrates the necessity to combine both requirements.
The requirement of a minimal compressive strength class is optional according to the standard. If the requirements of a minimum cement content and a maximum W/C ratio are combined, the requirement of a maximum compressive strength class is indeed optional for the investigated mixes.

Chloride penetration
For the verification of the applicability of the Standards EN 206-1: 2001 and NBN B15-001: 2004 on SCC concerning corrosion induced by chlorides from sea water, the experiments are agreeing with exposure class XS3 'Tidal, splash and spray zones – parts of marine structures'. This class requires at least a concrete type T(0,45). This means a maximum W/C ratio of 0.45, a minimum cement content of 340 kg/m³ and a minimal compressive strength class of C35/45. For the different concrete compositions, the chloride penetration depth after 50 years is calculated. In Table 5, the maximum penetration depth is given for each concrete type. From Table 5 it is concluded that indeed concrete type T(0,45) is needed to obtain a penetration depth which is smaller than 40 mm.
Again, the necessity to combine the requirement of a minimum cement content and a maximum W/C ratio is verified. It was also verified whether the compressive strength class is indeed an optional requirement. In Table 6, only the cement content is taken into account. From this Table, it is concluded that using a minimum cement content of 340 kg/m³ as the only requirement is not sufficient to obtain a chloride penetration of less than 40 mm.

Table 5. Maximum chloride penetration depth for different concrete types

		x (mm)
T(0,45)	SCC6	35.4
T(0,50)	SCC10	53.1
T(0,55)	SCC5	57.5
T(0,60)	SCC13	60.4

Table 6. Maximum chloride penetration depth for different cement contents

C (kg/m³)		x (mm)
300	SCC13	60.4
320	SCC13	60.4
340	SCC13	60.4

In Table 7, only the W/C ratio is taken into account. From the data in this Table it is concluded that the requirement of a maximum W/C ratio of 0.45 is sufficient to obtain a maximum chloride penetration depth of 40 mm.

Table 7. Maximum chloride penetration depth for different W/C ratios

W/C (-)		x (mm)
0,45	SCC6	35.4
0,50	SCC10	53.1
0,55	SCC5	57.5
0,60	SCC13	60.4

If only the compressive strength class is considered, it is concluded that it is not sufficient to require a minimum compressive strength class of C35/45 in order to obtain a maximum chloride penetration depth smaller than 40 mm. However, if the minimum cement content and the maximum W/C ratio are combined, it appears that the requirement of the compressive strength class is indeed optional.

CONCLUSIONS

Considering the applicability of the European Standard NBN EN 206-1: 2001 'Concrete – Specification, performance, production and conformity', for vibrated concrete, to SCC, the following conclusions can be drawn:

- Even though the SCC is outside the scope of the European Standard, the considered mixes are fulfilling the requirements concerning corrosion induced by carbonation and by chlorides from sea water.
- The combination of a maximum W/C ratio and a minimum cement content is necessary in the case of SCC. The requirement concerning the compressive strength class can be treated as optional in case of SCC.
- In almost all cases for the SCC studied in this research, there is a large difference between the minimum compressive strength class corresponding to the concrete type as defined in the Standard and the actual compressive strength class.

REFERENCES

1. K. Audenaert, 'Tranportmechanisms in self-compacting concrete in relation to carbonation and chloride penetration' (in Dutch), PhD, Ghent University, 2006, 370p
2. K. Audenaert, V. Boel, G. De Schutter: 'Carbonation of self compacting concrete', 6th International Symposium on Utilization of High Strength / High Performance Concrete, Leipzig, June 2002, p. 853-862
3. K. Audenaert, V. Boel, G. De Schutter, 'Carbonation of SCC', Third International Conference ConMat'05, August 22-24, 2005 - Vancouver, Canada
4. K. Audenaert, V. Boel, G. de Schutter, 'Carbonation of filler type self compacting concrete', 12th International Congress on the Chemistry of Cement, 8-13 July, 2007, Montreal, Canada
5. N. Otsuki, S. Nagataki, K. Nakashita, 'Evaluation of $AgNO_3$ solution spray method for measurement of chloride penetration into hardened cementations matrix materials', ACI Materials Journal, 89 (6) (1992) 587-592.
6. K. Audenaert, G. De Schutter, 'Chloride penetration by cyclic immersion of self-compacting concrete', 5th International RILEM Symposium on Self-Compacting Concrete, 3-5 September 2007, Ghent, Belgium
7. K. Audenaert, V. Boel, G. De Schutter, 'Chloride penetration in self compacting concrete by cyclic immersion', First International Symposium on Design, Performance and Use of Self Consolidating Concrete, May 26-28, 2005 – Changsha, China.
8. K. Audenaert, G. De Schutter, 'Study of chloride penetration in self-compacting concrete by simulation of tidal zone', accepted for ICCRRR 2008, November 24-26, 2008 – Cape Town, South Africa